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DEVELOPMENT OF METHODS FOR CALCULATION OF THE THERMAL REGIME OF ROCK-FILL DAMS IN REGIONS OF SEVERE CLIMATE

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DEVELOPMENT OF METHODS FOR CALCULATION OF THE THERMAL REGIME OF ROCK-FILL DAMS IN REGIONS OF SEVERE CLIMATE

N.A. Mukhetdinov

THESIS ABSTRACT

The most economical type of retaining structure in the regions of the far north is a dam made of local construction materials. This is true because of the availability of sufficient quantities of local construction materials, the possibility of using highly productive mechanisms for processing and placement of these materials in the structure with year-round continuation of construction operations.

A number of water-retaining structures have already been built of local construction materials in Siberia and the far north, the largest of these being the dams of the Vilyuyskaya and Khantayskaya Hydroelectric Power Plants. The experience gained in the operation of these dams has shown that complex processes of heat and mass transfer occur in them constantly, and determine, in the final analysis, the formation of the thermal regime of the structure. The temperature and moisture regime of dams erected in regions with severe climatic conditions goes far to determine the selection of the type of dam used and its structural peculiarities.

In spite of the successes which have been achieved in the area of planning, construction and operation of dams of local materials, erected in regions with severe climate, as was noted in the resolutions of the coordination conference on water engineering construction, a number of problems remain which require further study before today's requirements for planning and construction can be met.

One of these problems is the development of methods of calculation of the temperature and moisture regime of rock-fill dams considering the convection of air and water vapor through the pores in the fill with complex boundary conditions; this is the primary content of the present dissertation.

The work presents the theoretical and experimental (laboratory and natural) investigations of the author, revealing the processes of formation of the thermal regime of individual structural elements of a rock-fill dam (downstream prism, foundation, central impervious core and inclined impervious core).

The work was performed at the Siberian Affiliate of the All-Union Scientific Research Institute of Hydraulic Engineering imeni B. Ye. Bedeneyev in 1966-1971.

Chapter 1 studies the development and current status of theoretical and experimental studies on free convection in porous media, the determination of their heat and moisture exchange properties.

A rock-fill dam erected under difficult geological, geocyrological conditions of the base is an open thermodynamic system. The material and energetic interactions of the dam with its environment disrupt its thermal equilibrium, leading to the appearance of flows of heat, water, air and vapor in the dam. The intensity of the process of heat and material transfer is determined, in addition to the external factors, by the physical, mechanical and thermal-physical properties of the materials of the foundation and the elements of the dam (specific and volumetric heat capacity, coefficients of

conductive, radiant and convective heat transfer, aerodynamic and hydrodynamic resistance of the fill material, temperature and moisture conductivity coefficients). There are comparatively numerous experimental and theoretical works concerning all of these problems, as well as free air convection.

Analysis of the influence of free air convection on the thermal regime of a medium with large pores forms the subject of a work by M.E. Aerov and N.N. Umnik. They suggested a specific analytical dependence for determination of the effective (adjusted) heat and temperature conductivity coefficients, considering the intensification of heat transfer.

V.G. Gol'dman, G.V. Porkhayev, R.M. Sarkisyan, N.V. Ukhova and N.S. Ivanov analyzed free convection in the general process of heat exchange in calculating the thermal regime of thawing permafrost. However, the calculation formulas which they produced are correct only for

[Pages 4 and 5 missing – tr.]

Analysis of works on the study of free convection shows that the general equations of heat and mass transfer of free [illegible – tr.] of the air in materials with large pores have not yet been formulated, while the heat and mass conducting properties have been studied basically only for porous media with small particle diameters.

Further studies, both theoretical and experimental, are necessary to determine the regularities and nature of changes in the temperature-moisture regime of large-pore media.

In Chapter 2, the basic equations of heat and mass transfer are formulated relative to the downstream supporting prism of rock-fill dams, and methods of their numerical solution are analyzed.

In the thermodynamic respect, the downstream prism of a dam was analyzed as a heterogeneous multicomponent system, consisting of the mineral skeleton, water, water vapor and pore gases. The transfer of heat within this system is by heat conductivity, radiation and convection, the transfer of matter – by molecular and molar movement of vapor and liquid.

The heat and mass transfer equations were produced on the basis of the law of conservation of energy and matter, the law of changing momentum, under the condition that the transfer coefficients can be determined experimentally with the corresponding potentials.

The vapor space of natural large-pore media, particularly rock fill, has a complex and disordered structure.

The introduction of statistical characteristics of porosity, filtration rate, permeability and temperature allowed the flows to be homogenized within a small volume and the concepts of speed, pressure, permeability, temperature and mass at a given point to be introduced to the theory of heat and mass transfer. Therefore, the equations are correct for a fictitious medium with physical characteristics corresponding to the mean integral parameters of rather large volumes of actual fill. The boundary conditions of the equations of heat and moisture transfer are strictly determined only if, in addition to the equations produced, we also analyze equations describing the speed, moisture and temperature fields of air outside the dam considering the varying meteorological conditions.

Analysis of the results of observations of the dam of the Vilyuyskiy Hydroelectric Power Plant over a number of years has shown that the boundary condition at the surface of the downstream prism for the equation defining the velocity field of the air can be determined with accuracy sufficient for practice by setting the normal derivative of the flow function equal to 0, the temperature of the vapor-air mixture at the entry to the downstream prism equal to the external air temperature; moisture transfer has no significant influence on the formation of the thermal regime of the rock-fill downstream prism.

The system of equations for determination of the temperature regime of the downstream prism of a rock-fill dam can be reduced to the form:

$$
1\quad\begin{cases}
C_{vol}(x, y)\dfrac{\partial t}{\partial \tau} = \dfrac{\partial}{\partial x}\left[\lambda(x, y)\dfrac{\partial t}{\partial x}\right] + \dfrac{\partial}{\partial y}\left[\lambda(x, y)\dfrac{\partial t}{\partial y}\right] + dv(x, y, \tau)(\theta - t); & (1)\\[2ex]
\dfrac{\partial \theta}{\partial \tau} + \dfrac{1}{\rho m}\dfrac{\partial \psi}{\partial y}\dfrac{\partial \theta}{\partial x} - \dfrac{1}{\rho m}\dfrac{\partial \psi}{\partial x}\dfrac{\partial \theta}{\partial y} = \dfrac{dv(x, y, \tau)}{C_{vol}\, m}(t - \theta); & (2)\\[2ex]
\dfrac{\partial}{\partial x}\left(K_x\dfrac{\partial \psi}{\partial x}\right) + \dfrac{\partial}{\partial y}\left(K_Y\dfrac{\partial \psi}{\partial y}\right) = -\dfrac{\partial}{\partial x}(\gamma, \beta, m, \theta); & (3)\\[2ex]
\rho = \dfrac{\rho_0}{1 + \beta\theta} & (4)
\end{cases}
$$

The boundary conditions are:

1. The temperature at the permeable surface of the downstream prism

$$\frac{\partial t_{sur}}{\partial \tau} = \frac{dv(x, y, \tau)}{C_{vol}}(\theta_{sur} - t_{sur}) + \frac{1}{C_{vol}}\, q, \tag{5}$$

where $x = x_{sur}$
$y = y_{sur}$.

2. The temperature at the interfaces between the downstream prism and the other elements of the dam (central core, inclined core, foundation)

$$\lambda_k \frac{\partial t}{\partial n} = \lambda_{int}\frac{\partial t_{int}}{\partial n}\;;\quad t_{int} > t. \tag{6}$$

3. The temperature of the moving air at the boundaries of the downstream prism

a) $\theta(x, y, \tau) = \theta(x'_{sur}, y'_{sur}, \tau) = t_{ext}$

where $x = x'_{sur}$
$y = y'_{sur}$; (7)

b) $\theta(x, y, \tau) = \theta(x_{int}, y_{int}, \tau) = t(x_{int}, y_{int}, \tau)$,

where $x = x_{int}$
$y = y_{int}$.

4. The flow line function

a) $\psi = 0$,

where $0 < x < B, y = 0$ and $0 < y < H, x = 0$ (8)

b) $\dfrac{\partial \psi}{\partial n} = 0$,

where $x = x'_{sur}\,; y = y'_{sur}$;

c) $\psi = \text{const.}$

in the air-impervious sectors of the downstream prism.

The initial conditions are:

$$t(x, y, \tau) = t(x, y, 0);$$

$$t(x, y, \tau) = \theta(x, y, 0);$$

$$\psi(x, y, \tau) = \psi(x, y, 0) \tag{9}$$

where t, θ are the mean integral temperature of the rock fill and of the air, °C;

t_{sur}, θ_{sur} are the same, at the pervious surface of the downstream prism, °C;

t_{ext} is the temperature of the external air, °C;

ψ is the flow function, M^2/hr;

dv is the volumetric heat exchange coefficient, kcal/M^3 hr °C;

β is the coefficient of volumetric expansion of the air, 1/°C;

ρ is the density of the air, kg/M^3;

ρ_0 is the density of the air at 0°C, kg/M^3;

γ is the volumetric weight of the air, kg/M^3;

m is the porosity of the fill;

C_{vol}, C'_{vol} is the volumetric heat capacity of the fill and air, kcal/M^3 °C;

q is the quantity of heat carried into the dam by heat conductivity, kcal/M^3 hr;

$\lambda_k (\partial t/\partial n)$ is the heat flux from the downstream prism to the line of contact with elements of the dam, kcal/M^2 hr;

$\lambda_{int} (\partial t_{int}/\partial n)$ is the same, from the central core (inclined core), and base of the dam, kcal/M^2 hr;

λ_k is the coefficient of transverse convective heat conductivity, kcal/M hr °C;

λ_{int} is the same, for the base, central core (inclined core), kcal/M hr °C;

n is a perpendicular to the surface, M;

x_{int}, y_{int} are the coordinates of the interface of the downstream prism with the base, central core (or inclined core), M;

x_{sur}, y_{sur} are the coordinates of the surface of the downstream prism, M;

x'_{sur}, y'_{sur} are the coordinates of the surface of a fictitious layer, M;

B is the width of the downstream prism at the base, M;

H is the height of the downstream prism, M.

Equation system (1) was used to calculate the thermal regime of an isotropic and anisotropic rock-fill downstream prism.

In the isotropic prism, considering the nonlinearity of filtration of air with free convective motion, the coefficients of equations (1) and (3) were taken as:

$$C_{vol}(x, y) = C_{vol} = \text{const};$$

$$m(x, y) = m = \text{const};$$

$$\lambda(x, y) = \lambda_{ef} = \text{const}.$$

$$K_x = K_y - f(\rho w) \begin{cases} \mu/\rho k, \text{ at Re} = \text{Re}_{cr} \\ 1/\rho\,[(\mu/k) + B_0 \rho w), \text{ at Re} > \text{Re}_{cr} \end{cases} \tag{10}$$

where λ_{ef} is the coefficient of heat conductivity of the fill, kcal/M hr °C;

μ is the dynamic viscosity factor of the air, kg hr/M^2;

K is the coefficient of permeability of the fill, M^2;

B_0 is the turbulence parameter, kg/M^4;

Re is the Reynolds number;

Re_{cr} is the critical Reynolds number, defining the transition of the air flow from one mode to the other.

2. In an anisotropic downstream prism, the coefficients of equation (3) are

$$Kx = Ky = \frac{\mu}{\rho K(y)} ;$$

$$m = m(y) ;$$

$$C_{vol} = C_{vol}(x, y). \tag{11}$$

Equation system (1) includes nonlinear equations of parabolic (1), hyperbolic (2) and elliptical (3) types. Solution of the system of nonlinear equations in analytic form is possible only in exceptional cases. The universal method of approximate solution of differential equations is the method of finite differences, which was used in performing our calculations. The author has developed a special method of numerical solution for the quasilinear elliptical equation describing the motion of air considering the nonlinearity of filtration.

The equation of nonlinear filtration (3), considering (10), is reduced to the form:

$$\frac{\partial}{\partial x}\left[\frac{1}{\rho_0}\left(\frac{\mu_0}{K} + B_0|w|\right)\frac{\partial \psi}{\partial x}\right] + \frac{\partial}{\partial y}\left[\frac{1}{\rho_0}\left(\frac{\mu_0}{K} + B_0|w|\right)\frac{\partial \psi}{\partial y}\right] = -g\beta m\,\frac{\partial \theta}{\partial x} \tag{12}$$

where ρ_0, μ_0, β_0 are the density, viscosity and coefficient of volumetric expansion of the air corresponding to the average temperature of air moving through the pores over the profile of the downstream prism.

Let us introduce the function

$$\phi(x, y, \tau) = \int_0^{\psi} \frac{1}{\rho_0\beta_0 g m}\left(\frac{\mu_0}{K} + B_0|w|\right)\partial\psi .$$

Equation (12) is transformed to

$$\frac{\partial^2\phi}{\partial x^2} + \frac{\partial^2\phi}{\partial y^2} = -\frac{\partial\theta}{\partial x} . \tag{13}$$

This equation should be solved with the boundary and initial conditions

$$\phi = 0, y = 0, 0 < x < B; x = 0, 0 < y < H;$$

$$\frac{\partial\phi}{\partial n} = 0, \text{ where } x = x'_{sur}, y = y'_{sur};$$

$$\phi(x, y, \tau) = \phi(x, y, 0). \tag{14}$$

The numerical solution of equation (13), considering boundary conditions (14), is usually produced by finite-difference methods using a plan of traveling calculation and simple iteration. The solution of this equation was considered to be found if the difference in two successive approximations satisfied the condition

$$\left| \, |\phi_{n+j}^{S+1}| - |\phi_{n,j}^{S}| \, \right| < \epsilon , \tag{15}$$

where S is the number of iterations;

ϵ is a predetermined comparison constant.

Based on the known values of function $\phi(x, y, \tau)$ at discrete points in the area in question, the following algebraic equations were produced for determination of the flow function:

$$1.\ g\beta_0 m\phi_{n,j} = \frac{\nu_0}{K}\psi_{n,j} + \frac{B_0}{\rho_0}\left[\frac{(2C\psi_{n,j}+\eta)}{4C}\sqrt{C\psi_{n,j}^2+\eta\psi_{n,j}+a}\right.$$

$$\left. + \frac{(4aC-\eta^2)}{8C\sqrt{C}} \times \mathrm{Arsh}\left(\frac{2C\psi_{n,j}+\eta}{\sqrt{\Delta}}\right) - \eta\frac{\sqrt{a}}{4C} - \frac{(4aC-\eta^2)}{8C\sqrt{C}}\,\mathrm{Arsh}\frac{h}{\sqrt{\Delta}}\right]; \tag{16}$$

$$2.\ g\beta_0 m\phi_{n,j} = \frac{\nu_0}{K}\psi_{n,j} + \frac{B_0}{\rho_0}\left[\frac{(2C\psi_{n,j}+\eta)}{4C} - \sqrt{C\psi_{n,j}^2+\eta\psi_{n,j}+a} - \frac{\eta\sqrt{a}}{4C}\right], \tag{17}$$

where ν_0 is the coefficient of kinematic viscosity of the air corresponding to the average temperature of air moving through the pores across the profile of the downstream prism, M^2/hr;

$$C = \left(\frac{1}{\Delta x^2} + \frac{1}{\Delta y^2}\right);$$

$$\eta = -2\left(\frac{\psi_{n-1,j}}{\Delta x^2} + \frac{\psi_{n,j+1}}{\Delta y^2}\right);$$

$$a = \left(\frac{\psi_{n-1,j}^2}{\Delta x^2} + \frac{\psi_{n,j-1}^2}{\Delta y^2}\right). \tag{18}$$

Arsh is the reciprocal value of the main hyperbolic sine.

The stability and convergence of the finite-difference plans for equation system (1) are defined from the conditions:

$$1 - \left[\left(\frac{(\lambda_{n+1,j}+\lambda_{n-1,j}}{\Delta x^2} + \frac{(\lambda_{n,j+1}+\lambda_{n,j-1})}{\Delta y^2} + dv,n,j\right)\frac{\Delta\tau}{C_{vol,n,j}}\right] > 0$$

$$1 - \left[\left(\frac{\Delta\tau}{m\Delta x\Delta y}\,max\,(\psi_{n,j}-\psi_{n,j-1})\right) + \left(\frac{\Delta\tau}{m\Delta x\Delta y}\,max\,(\psi_{n,j}-\psi_{n+1,j})\right)\right] > 0, \tag{19}$$

where $\lambda_{n,j+1}; \lambda_{n,j-1}; \lambda_{n+1,j}; \lambda_{n-1,j}$ is the heat conductivity coefficient of points with the corresponding indices, kcal/M hr °C.

Chapter 3 presents the results of experimental studies of physical-mechanical and heat-physical properties of a rock fill.

Processing of the results of laboratory experiments and field studies allowed the production of empirical equations for determination of:

– the surface area (F) of an individual unit of fill volume

$$F = \frac{7.2\,(1-m)}{d}, \tag{20}$$

where d is the calculated mean diameter of an individual rock, M;

– the mean characteristic dimension (R_v) of the fill

$$R_v = \frac{d}{13.5\,(1-m)}, \tag{21}$$

– the aerodynamic resistance (f_p) of the large pore fill

$$f_p = \frac{430}{\mathrm{Re}} + 0.85, \tag{22}$$

– the coefficient of permeability (k) (where $d > 10$ cm)

$$K = \frac{d^2 m^3}{3100\,(1-m)^2}, \tag{23}$$

– the turbulence parameter (B_0)

$$B_0 = 0.83\,\frac{(1-m)\rho}{dm^3}. \tag{24}$$

The heat conductivity coefficient of the fill (λ_{ef}) is satisfactorily described by the formula of V.I. Odelevskiy.

The temperature conductivity coefficient (a_ϕ) is defined as the derivative of a quantity:

$$a_\phi = \frac{\lambda_{e\phi}}{C_{vol}}. \tag{25}$$

The volumetric heat capacity (C_{vol}) of the fill was found using the formula

$$C_{vol} = (1-m)\,C_{sp}\,\gamma_{ck} + mC'_{vol}, \tag{26}$$

where C_{sp} is the specific heat capacity of the material of the rock fill, kcal/kg °C;

γ_{ck} is the volumetric weight of the material of the rock fill, kg/M^3.

Equations (20-26) allow us to determine all of the parameters of the two-phase rock fill which we will need.

In Chapter 4, results are presented from calculation of the influence of nonlinear filtration of air on the formation of the thermal regime of the rock-fill downstream prism and the calculated

values of temperature are compared with the data of field observations of the rock-fill dam of the Vilyuyskaya Hydroelectric Power Plant.

In determining the thermal regime of the dam of the Vilyuyskaya Hydroelectric Power Plant, two structural models of the downstream prism were analyzed:

a) Anisotropic, when the mean calculated diameter of individual rocks and the porosity of the fill in the vertical plane were taken as functions of coordinates, but they were considered constant in any horizontal plane;

b) Isotropic, with porosity and diameters of individual rocks corresponding to the mean values of the anisotropic fill.

The upstream shell, foundation, and inclined core were looked upon as a rigid body with varying heat-physical characteristics, in which heat transfer occurs only by conduction. The latent heat of phase transitions during freezing (and thawing) in the inclined core and upstream shell were considered by a method developed by Yu. Ye. Gavrish and L.N. Khrustalev. Filtration of air in the downstream prism was considered by the rule of Darcy.

The filtration anisotropy of the downstream prism of the dam leads to redistribution of the air flow, qualitative and quantitative changes in its thermal regime, particularly in areas near the slope and foundation of the dam. In an anisotropic fill, in comparison with an isotropic fill, the concentration of flow lines at the foundation shows that the main paths of movement of air in the downstream prism are sections of the fill with large diameters of individual rocks and high porosity. As we move away from the surface of the slope, the influence of anisotropy on the formation of the thermal regime of the downstream prism decreases. In the zone beneath the inclined core, the temperature fields produced by calculations for both media are almost identical or differ little from each other, and also agree closely with the observed data.

The difference in temperature between the calculated and observed data was: in the zone beneath the inclined core ±2°C and in the surface zone of the downstream prism ±4°C. The main reason for the difference, as observations showed, was the diurnal and weekly fluctuations in temperature, leading to changes in the direction of air flow within the body of the downstream prism. The predominant direction of natural movement of the air flow in the downstream prism is determined by the external air temperature. In the water, the flow enters at the base and leaves through a sector near the top of the dam, while in the summer the air flow is in the opposite direction. In accordance with this, in moderate or high head dams, in the upper half of the downstream prism the temperature of the fill changes its sign during the course of the year, while in the lower half of the downstream prism in areas with year-round negative temperatures, the temperature remains negative [below freezing] constantly. In the fall, during a period of 1.5-3 months, we see a shift in the isotherms of negative temperature toward the impervious elements of the dam.

The rate of change of the thermal regime of the downstream prism can be regulated by placement of an air-impervious blanket on its slope. The primary effect of the air-impervious blanket is that it excludes convective heat exchange in the downstream prism with the atmosphere. The rate of movement of the air in the pores is greatly decreased, the mean temperature of the fill changes more slowly than in dams with free air exchange.

In Chapter 5, a study is made of individual problems of the thermal regime of the core and foundation of a rock-fill dam. The core of a rock-fill dam experiences the influences of complex processes of heat exchange, occurring at the surface of the dam, in the supporting downstream prism, and also in the upstream shell, which is in thermal interaction with the reservoir. In planning and construction of rock-fill dams, it is important to establish the general trend of formation of the thermal regime of the core and foundation of the dam, if possible considering all of the factors mentioned.

The formation of low negative temperatures in the fill of the downstream prism and their maintenance throughout the year creates conditions for freezing of the foundation of the rock-fill dam. Depending on the dimensions of the downstream prism, the "aureole" of freezing of the nonfiltering

foundation of the dam may become significant. It can be determined quantitatively by the method of calculation of thawing beneath industrial and civil structures.

Under more complex conditions of mass transfer, a zone of negative temperature is formed in filtering foundations, and depends not only on the size of the downstream prism and temperature at the base (t_b), but also on the filtration factor (K_f), the heat and temperature conductivity of the soil of the base when thawed and frozen (λ_t, a_k λ_m), the head (H) and temperature of the bottom layers of water in the reservoir (t_{wat}). However, the formation of an "aureole" of freezing in the foundations of rock-fill dams creates the effect of a cut-off in relationship to the filtration flow. This decreases the filtration flow passing through the foundation.

The maximum freezing depth of the foundation of the dam with filtration heat transfer is displaced in the downstream direction and can be determined from the equation

$$\frac{\xi_{max}}{\ell_1} = f\left(\pi \frac{\lambda_m t_b \sqrt{a_k}}{\lambda_t t_{wat} \sqrt{K_f A}}\right)$$

where ξ_{max} is the maximum depth of freezing of the foundation beneath the downstream prism, M;

ℓ_1 is half the length of the horizontal subterranean contour of the dam, M.

Studies have shown that the temperature of the filtering flow in the foundation at the lower face of the core differs very little and is always lower than the temperature of the water in the reservoir.

Reverse filters, in which heat is propagated only by conduction, significantly decrease the cooling influence of the downstream prism on the impervious elements.

The minimum thickness of a reverse filter providing for exit of filtration water at 0 head can be determined by the following approximate formula:

$$\ell \cong \frac{\lambda_{ef}^H t_{min}^H (\lambda_3 + G C_{vol} h)}{\lambda_3 G C_{wat} t_{wat}}, \tag{28}$$

where ℓ is the thickness of the reverse filter, M;

λ_{ef}^H is the effective heat conductivity coefficient of the material of the reverse filter, kcal/M hr °C;

t_{min}^H is the minimum temperature of the fill of the downstream prism at the boundary with the reverse filter, °C;

λ_3 is the heat conductivity factor of the first layer of the filter in the thawed state, kcal/M hr °C;

G is the flow rate of water at the line of the surface of the core, kg/M^2 hr;

t_{wat} is the temperature of the water in the reservoir, °C;

C_{wat} is the specific heat capacity of the water, kcal kg/°C;

h is the distance from the surface of the water filtering through the downstream face of the core to the 0 isotherm, M.

Under the cooling influence of the downstream prism, the core is frozen (filtration is stopped) in dams in which the flow rate of water through the core is less than that calculated by the formula:

$$G < -\frac{\lambda_{ef}^H t_{min}^H}{(C_{wat} t_{wat} + q_\phi)\ell}, \tag{29}$$

where q_ϕ is the latent heat of phase conversion, kcal/kg.

CONCLUSIONS

1. Physical equations are produced for the heat and mass transfer in the downstream prism of a rock-fill dam, and conditions of unambiguity of these equations are established.

2. Based on actual observations, the possibility is established of simplification of the boundary conditions of equations describing the temperature-moisture regime of the downstream prism.

3. Quantitative relationships are established for the change in surface area of individual rocks in a unit of fill volume, the mean characteristic diameter, aerodynamic resistance and heat-physical characteristics of the rock fill.

4. A method is developed for calculation of the temperature fields of rock-fill dams considering:

– The thermal and filtration anisotropy of the downstream prism;

– The conditions of heat exchange of a rock-fill downstream prism with the surrounding environment, variable in time and space;

– Heat transfer of the filtering flow of water in the foundation and the core of the dam;

– The engineering geological, geocryological conditions of the foundation and the geometric forms of dam elements;

– Nonlinearity of filtration with free convective motion of air in large-pore media.

5. An algorithm has been written and calculations performed on a computer to determine the thermal regime of the rock-fill dam of the Vilyuyskaya Hydroelectric Power Plant for anisotropic and isotropic models of the downstream prism.

The results of the calculation and the data of actual observations agree closely.

6. The anisotropy of the downstream prism, resulting from the technology of work involved in placing the rock fill in layers, leads, in comparison to an isotropic prism, to qualitative and quantitative redistribution of the air flow and temperature in the prism only in areas near the downstream slope.

7. Intensive change in the thermal regime of the downstream prism of rock-fill dams occurs during the first two months after the outside air temperature falls below the freezing point.

8. In rock-fill dams erected in severe climatic regions with free air exchange between the downstream prism and the atmosphere, two characteristic thermal regime zones are formed:

– The upper portion of the downstream prism, where the temperature rises above and falls below freezing during the year;

– The lower portion of the downstream prism, where the temperature remains below freezing throughout the year.

9. An air-impervious blanket on the surface of the downstream prism has a significant influence on the overall thermal regime of rock-fill dams. The absence of convective heat exchange between the downstream prism and the outside air during the summer results in cooling and, during the winter – in warming of the overall temperature of the rock-fill dam.

10. Calculations have shown that:

– The natural thermal regime of a rock-fill downstream prism, even if filtration is eliminated, does not provide the freezing of all impervious elements of a frozen type dam required for safe use;

– Elimination of periodic freezing of the core in dams of this type and free passage of water filtering through the core can be assured by proper selection of the necessary thickness of reverse filters.

11. Studies of the freezing of the filtering foundation of a rock-fill dam have established that:

– In dams with moderate or high head, the temperature of the water filtering into the foundation beneath the central core (or inclined core) is close to the temperature of the water in the reservoir;

– The maximum freezing depth of the foundation of the dam is displaced from the downstream slope by a distance of 2/3 of the half length of its underground contour;

– The freezing of the bed beneath the downstream prism of a rock-fill dam significantly decreases or even eliminates filtration in the foundation of the structure.

BASIC POSITIONS OF THIS DISSERTATION PUBLISHED IN THE FOLLOWING ARTICLES

1. Mukhetdinov, N.A., "Thermal regime of the downstream prism of a rock-fill dam," *Izvestiya VNIIG*, vol. 90, 1969.
2. Mukhetdinov, N.A., "Some problems of the thermal regime of a rock-fill dam," *Trudy VI Soveshchaniya-Seminara po Obmenu Opytom Stroitel'stva v Surovykh Klimaticheskikh Usloviyakh*, vol. 8, Krasnoyarsk, 1970.
3. Mukhtedinov, N.A., "Calculation of the thermal regime of the downstream prism of a rock-fill dam," *Nauchnyye Soobshcheniya*, no. 9, Materials of Conference of Young Specialists, Krasnoyarsk, 1970.
4. Mukhetdinov, N.A., "Influence of nonlinear air filtration on the thermal regime of a rock-fill dam," *Izvestiya VNIIG*, vol. 96, Leningrad, 1971.

RESULTS OF WORK REPORTED AT

1. First Regional Conference of Young Scientific Workers of Krasnoyarsk Kray, Krasnoyarsk, 1969.
2. Coordination Conference on Temperature-Moisture Regime of Dams Made of Local Materials, Krasnoyarsk, 1969.
3. VI All-Union Conference-Seminar for Exchange of Experience of Construction under Severe Climatic Conditions, Krasnoyarsk, 1970.
4. Section of Scientific Council of Section on Underground Structures, Foundations and Soils, VNIIG imeni B. Ye. Vedeneyeva, 1971.